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PERFORMANCE OF THE FW-4 THIRD STAGE MOTOR DELTA 38

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GREENBELT, MARYLAND

X-470-67-117

PERFORMANCE OF THE FW-4 THIRD STAGE MOTOR DELTA 38

February 21, 1967

NASA, Goddard Space Flight Center
Greenbelt, Maryland

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PERFORMANCE OF THE FW-4 THIRD STAGE MOTOR DELTA 38

By

T. Stuart
Delta Project Office

SUMMARY

This report presents the results from the performance instrumentation on the third stage of Delta 38, the first Delta launch vehicle to use the FW-4 as the third stage motor.

The performance instrumentation showed a near-nominal pressure and acceleration record. A telemetry signal shift just prior to third stage ignition, causing a base line shift on the oscillograph records, contributed to a lower than expected total impulse as calculated from the chamber pressure and the thrust-time integral. Specific impulse calculated from orbital reconstruction (283 lbsF-sec/lbsM) was lower than obtained from simulated altitude tests at AEDC (285 lbsF-sec/lbsM). However, it was comparable with average results obtained from Scout Flights (283.7 lbsF-sec/lbsM). No evidence of a pressure disturbance was detected during tailoff and burnout. After burnout the calculated coning half angle of less than one degree was well below the acceptable level. Measured external FW-4 case temperatures were within the specified maximum tolerance of 500°F for 200 seconds after burnout.

ACKNOWLEDGEMENTS

The author is indebted to L. A. Williams of the Test and Evaluation Division for the reduction and display of the resultant data and to Robert Conrad of the Sounding Rocket Instrumentation Branch for his direction of the fabrication, assembly, and checkout of the system. The author also wishes to thank the other members of the Delta Project for their work on the telemetry system and their assistance in reducing the data.

PERFORMANCE OF THE FW-4 THIRD STAGE MOTOR DELTA 38

INTRODUCTION

The Delta Project's program to uprate the performance of the Delta launch vehicle has led to the adaptation of a new third stage solid rocket motor, the FW-4. The purpose of this report is to present the in-flight performance data for the first FW-4 third stage motor flown on Delta.

Previous third stage solid motors on Delta have experienced differences in flight performance with respect to static test performance.[1] The magnitude of the differences is extremely important in establishing the performance predictions for individual missions. To determine the flight environment effect, third stage performance telemetry (PTM) was added to the Delta 38 (AE-B) launch vehicle for the maiden flight of the FW-4 motor. Performance parameters measured were: acceleration, chamber pressure, case temperature, coning, spin rate, and chuffing.

The FW-4 performance evaluation was implemented by the Goddard Space Flight Center (GSFC) as a secondary objective. The primary objective was to launch into orbit the Atmospheric Explorer (AE-B) satellite.[2] The AE-B spacecraft is designed to measure the density, composition, pressure, and temperature of the earth's atmosphere, and the variation of these parameters with the time of day. The satellite was launched on the three stage Delta vehicle (DSV-3C) from Pad 17B of the Eastern Test Range (ETR) on May 25, 1966.

VEHICLE DESCRIPTION

The three-stage Delta DSV-3C-1 vehicle is illustrated in Figure 1.[3]

The new third stage is a United Technology Center (UTC) FW-4 solid propellant motor.[4] Attitude control for this final stage is achieved by spin stabilizing the third-stage and spacecraft combination prior to separation from the second stage. A fitting is attached to the shoulder on the forward end of the third stage motor to support the spacecraft. The spacecraft attach fitting includes provisions for separating the spacecraft at the support structure interface. A spring is used to produce a velocity differential between spacecraft and motor case.

The Delta 38 (AE-B) was the first mission to utilize the FW-4 motor. Figure 2 shows the FW-4 profile.

Modifications to the third stage for this flight were:

1. A rocket motor designated FW-4S, normally used on the Scout vehicle was flown. The "-S" configuration differs from the Delta "-D" configuration only in the aft attachment ring.
2. The forward dome and sides of the FW-4 motor were covered with aluminum foil to provide thermal protection to the instrumentation equipment and act as an antenna ground plane.
3. A tumble system was provided, to tumble the third stage away from the spacecraft after spacecraft separation.
4. A PTM package was installed on the forward attach ring.

Table 1 lists the nominal dimensions and predicted performance of the vehicle by stages.

Table 1
Nominal Dimensions and Predicted Performance
Characteristics of the Delta Vehicle by Stages

Characteristics	Stage I Mod. Thor Missile Rocketdyne MB-3 Block III	Stage II Aerojet General AJ10-118D	Stage III UTC FW-4S
Overall Length	59.67 ft.	23.12 ft.	58.43 in.
Principle Diameter	96 in.	33 in.	19.6 in.
Loaded Motor Weight	135,682 lbs.	5,865 lbs.	660.5 lbs.
	Liquid	Liquid	Solid
Type Propellant	LOX and RJ-1	IRFNA/UDMH	UTP-3096A
Propellant Weight	128,830 lbs.	4,688 lbs.	606.8 lbs.
Specific Impulse (Operational)	$\frac{\text{lbF-sec}}{\text{252 lbm}}$	$\frac{\text{lbF-sec}}{\text{267 lbm}}$	$\frac{\text{lbF-sec}}{\text{285 lbm}}$
Total Impulse (Operational)	25,100,000 lbF-sec	1,200,000 lbF-sec	174,000 lbF-sec
Average Thrust (Operational)	172,000 lbs.	7,550 lbs.	6,000 lbs.
Total Burn Time	149	174	31.5
Fuel to Oxidizer Ratio	2.15:1	2.76:1	———
Nozzle Expansion Ratio	8:1	20:1	50:1

Table 2 lists the nominal sequence of events.[2]

Table 2
Sequence of Flight Events

T + Sec	Min:Sec	Event
T + 0	00:00	First Stage Ignition
T + 150	02:30	MECO (Main Engine Cut Off)
T + 154	02:34	First Stage/Second Stage Separation and Second Stage Ignition
T + 318.6	05:18.6	SECO (Stage II Engine Cut Off)
T + 474	07:54	Fire Spin Rockets
		Start Stage III Ignition Time Delay
		Start Time Delay for Stage III Wire Cutters
T + 475	07:55	Fire Stage III Ignition Wire Cutters
T + 476	07:56	Blow Stage III/II Separation Bolts
		Fire Retros
T + 489	08:09	Stage III Engine Ignition
T + 519:5	08:39.5	Stage III Burnout
T + 600	10:00	Spacecraft/Stage III Separation
		Start YO Release Time Delay
T + 602	10:02	Release YO Weight

INSTRUMENTATION

Physical Description

The AE-B/Delta 38 third stage telemetry (AE-B/PTM)[5] consisted of four major assemblies attached to the FW-4 forward attach ring. System components were mounted on lightweight welded aluminum chassis which rested on the attach fitting lower flange. Flanges gussets and stiffeners tied the lower sections of each chassis to taped holes in the motor forward flange for rigidity.

The chamber pressure gauge mounted on the forward dome, temperature gauges at key locations on the motor case and the PTM telemeter antennas on the aft end of the motor complete the telemeter package. The entire TM system weighed 10.9 pounds. Component distribution on the various chasses was determined on the basis of related electrical functions and complementary weight balance consistent with good telemetry design practices. Details of the AE-B/PTM are shown in Figure 3.

Electrical Description

The third stage performance telemetry was a 7-channel FM/FM telemetry system utilizing a nominal 2-watt frequency modulated transmitter radiating at 256.2 mHz operating into a four-element turnstile antenna. All elements conformed to IRIG standards. Data from 21 temperature gauges were subcommutated by a 30-segment mechanical commutator operating at 2-1/2 rps in a standard IRIG format. All other channels were continuous.

A block diagram of the AE-B/PTM is given in Figure 4. Channel assignments are listed in Table 3.

Severe weight limitations on the AE-B/PTM precluded the use of a standard in-flight calibrator. Therefore, an inverse calibration technique which makes use of the existing commutator and its built-in calibration points was employed.

The input signal to each voltage controlled oscillator (VCO) to be calibrated was cross-strapped to a separate segment on the commutator. Thus, once each commutator frame, for each VCO, these data were transmitted over the commutator VCO as well as over their normal continuous channels. The level of the commutator data can then be used to define the voltage level accurately on that particular channel, at that particular time.

Table 3
AE-B/PTM
Third Stage Telemeter
Channel Assignments

Data	Symbol	Transducer	FS Range	IRIG Band	Band-Width
Longitudinal Vibration (FWD Flange)	$\ddot{X}_L$	Endevco 2221 D	±8g	E 70.0 KH_z ±15%	2100 H_z
Radial Acceleration (High Freq)	A_{RH}	Kistler 303A	+8/ -4g	C 40.0 KH_z ±15%	1200 H_z
Motor Case Temperature (21 Locations)*	TC-1 -21	Trans-Sonic T 4596	75-800 0_F	14 22.0 KH_z ±7-1/2%	330 H_z
Longitudinal Acceleration (High Range)	A_{LH}	Kistler 303A	+161 -4g	13 14.5 KH_z ±7-1/2%	220 H_z
Radial Acceleration (Low Freq)	A_{RL}	Kistler 303A	+4/ -3g	12 10.5 KH_z	160 H_z
Longitudinal Acceleration (Low Range)	A_{LL}	Kistler 303A	±1g	11 7.35 KH_z ±7-1/2%	110 H_z
FW-4 Chamber Pressure	P_C	Bourns 725	0-800 PSIA	10 5.4 KH_z ±7-1/2%	81 H_z

* PAM-Commutated – 30 Segments, 2½ rps
Accelerometer References:
Long. + Thrust – Drag
Radial + Outward – Inward

The AE-B/PTM antenna was a four-element turnstile array located near the aft end of the FE-4 motor case. Dipole elements are light spring-steel wires, mounted to fiberglass standoff brackets, epoxied to the motor case. The dipole elements were 90° apart and are normally straight, pointing perpendicularly away from the motor case. The antenna and harness assembly weighed 7.5 oz.

FW-4S MOTOR PERFORMANCE

Pressure

Figure 5a is a record of the FW-4S chamber pressure (Pc) with time, as reduced from the received telemetry signal, demodulated, and displayed on an oscillographic paper record. As is evident from the oscillograph record, a telemetry signal shift occurred at approximately third stage spinup. Resolution of the resulting base line shift could not satisfactorily be developed. Integration of the pressure-time curve over the action time for the telemetry trace, as received gave the values in Table 4.

Table 4
FW-4S Chamber Pressure

Action Time (Ta-sec.)	Chamber Pressure Integral $\left(\int_{To}^{Ta} \text{Pdt-PSIA-sec}\right)$	Average Chamber Pressure (PSIA)	Maximum Chamber Pressure (PSIA)
30.3	19,580 ± 3%	646	777

Longitudinal Acceleration

Figure 5b is an oscillograph record of the accelerometer signal as it was received. The resultant curve was then integrated using a planimeter to determine the total acceleration-time area; the same telemetry signal shift was evident in the accelerometer trace as in the pressure trace and handled in the same manner.

$$V = \int_{To}^{Ta} Adt$$

where:

V = incremental velocity, ft/sec

Ta = end of action time

To = start of burning time

A = acceleration, ft/sec

The average incremental velocity obtained by this method was 6465 feet/second.

From the results of the incremental velocity measurement, an estimate can be made of the propellant specific impulse:

$$\Delta V = gIsp\ Ki\ \ln \frac{Wi}{Wo}$$

$$Isp = \frac{\Delta V}{g\ Ki\ \ln \frac{Wi}{Wo}}$$

where:

g = gravitational constant, ft/sec

Isp = specific impulse, $\frac{\text{lbf-sec}}{\text{lbm}}$

Wo = initial weight, lb

Wi = final weight, lb

Ki = propellant weight/total expended weight.

The specific impulse equivalent to the average incremental velocity obtained was calculated at 281.85 lbf-sec/lbm, based upon the AE-B spacecraft weight, the manufacturer's stated propellant weight, and an estimated 3.5 pounds of inert weight consumed.

Orbital Reconstruction

The incremental velocity delivered by the third stage motor can be determined from the radar coordinates of the vehicle just prior to third stage ignition and the orbit obtained by the spacecraft.

A specific impulse, corresponding to this incremental velocity, can be calculated in the same manner as for the longitudinal acceleration. The specific impulse determined in this manner was 283.0 lbf-sec/lbm.

Constructed Thrust-Time Curves

From the results of the longitudinal acceleration records and the pressure transducer records, it is possible to construct thrust-time curves. Assuming a linear decrease in mass with burning time, knowing the initial starting mass, and estimating the final or consumed weight, the corresponding thrust level can be calculated, on a point-by-point basis, as a function of time. In a similar manner, the motor, $C_f A_t$ (where C_f is the thrust coefficient, and A_t is in the area of the throat) can be obtained from the ratio of thrust (F) to chamber pressure (Pc) measured during static tests. The $C_f A_t$ obtained can be used to calculate from the pressure data, the corresponding thrust level. The results of the comparison of these calculations are shown in Figure 6. The equations used were:

$$F_1 = MA$$

Where A is from telemetered data

$$F_2 = C_f A_t P_c$$

Where P_c is from telemetered data

Radial Acceleration

Figure 7a is an oscillographic record of the radial acceleration signal. The output of spin is evident from inspection of this record. The rate of spin can be calculated from the following formula:

$$a = W^2 R$$

where:

a = deflection rate, in/sec.

$W = (2\pi f)^2$

f = spin rate, cycles/sec.

R = radius, inches

Calculations made from the measured radial acceleration deflection give spin rates of 97.3 rpm at spinup increasing to 99 rpm at third stage burnout.

Low Level Longitudinal Acceleration (Coning)

Figure 7b is the oscillographic record of the low level longitudinal acceleration (+1g to -1g). From the low level longitudinal acceleration record, the coning amplitude and frequency of the third stage motor at burnout can be measured. The coning half-angle can be calculated by the following equation:

$$\lambda = \frac{Al\ (max.)}{P\ (\Omega^2 - \phi^2)}$$

where:

λ = coning

Al (max.) = longitudinal acceleration amplitude, ft/sec.

P = radius, ft.

Ω = third stage spin rate, radians/sec.

ϕ = frequency of sine wave of Al, radians/sec.

As is evident from the inspection of the record, the coning half-angle at burnout was small. A coning half-angle of less than one degree was calculated from the data. The coning was too small to be measured during the FW-4 operation period.

Case Temperature

Figure 8 is a plot of the FW-4 external case temperature during and after third stage operation with respect to the location on the motor. Temperatures were obtained until 400 seconds after third stage ignition on the igniter boss, forward and aft case domes, case cylindrical section, and the nozzle attach flange.

The highest temperature was recorded on the metal nozzle attach flange. The temperature at this point reached a maximum of 558°F at 380 seconds after ignition, and 502°F at 230 seconds after ignition.

The maximum temperatures recorded on the case proper were approximately 500°F at 400 seconds after ignition, and 440°F at 230 seconds after ignition in both the central and aft cylindrical areas.

The igniter boss underwent a 25°F temperature rise immediately after ignition, but cooled down prior to burnout. The igniter boss recorded the lowest maximum temperature 252°F at 400 seconds after ignition.

The case domes achieved an approximately equal temperature rise, with the temperature slightly higher on the aft dome. Heating on the domes increased as the distance from the motor centerline increased.

It should be noted that the FW-4S motor on this flight was wrapped with aluminum foil. Previous third stage motors wrapped with foil and tested at AEDC have experienced an additional temperature rise of 100°F due to the foil.

Flight-time History

The total vehicle flight was normal with one exception - the failure of the inertial radio guidance ground station to send second stage command shutdown. Shutdown of the second stage resulted from oxidizer depletion and hence a higher than nominal orbit was achieved. Tracking data established the following third stage performance:[6]

	Expected	Actual
Third stage burn time	30.5 sec.	30.75 sec.
Initial spin rate	93 rpm	97 rpm
Final spin rate	27 rpm	30 rpm
Time at spin up	T + 472.6 sec.	T + 471.4 sec.
Time at third stage ignition	T + 487.6 sec.	T + 485.75 sec.
Time at third stage burnout	T + 518.1 sec.	T + 516.5 sec.
Time at spacecraft separation	T + 598.6 sec.	T + 596.5 sec.

The orbital parameters, as calculated from the first two passes are as follows:

	Expected	Actual
Apogee (NM)	650	1468
Perigee (NM)	146	154
Inclination (deg.)	64.0	64.6
Period (min.)	99.5	116

CONCLUSIONS

The FW-4S flight chamber pressure and longitudinal acceleration were close to the expected established nominal from altitude spin tests at AEDC.[7]

The manually integrated accelerometer records give an average incremental velocity of 6,465 ft/sec., which is equivalent to a specific impulse of 281.9 lbf-sec/lbm. This compares with a specific impulse, computed from orbital reconstruction data, of 283.0 lbf-sec/lbm. The difference in value is considered within the accuracy associated with the method of data reduction. However the 283.0 value is given more credence since an unknown calibration error was introduced with the unexplained telemetry shift. The orbital reconstructed value is from 1.4 to 2.5 seconds low when compared with AEDC spin tests. However, 283 compares favorably with Scout FW-4S[8] flight data where the average specific impulse obtained from orbital reconstruction is 283.71 lbf/sec/lbm.

The integrated pressure time record gave 19.580 psia-seconds, which is again low when compared with AEDC tests. Most of this difference can be explained by the shorter action time of this motor (30.3 seconds) when compared with an AEDC action time of 30.5 seconds, for an FW-4 of comparable thrust level.

The achieved spin rate of the motor calculated at 98 rpm average, was well within the allowable ± 10% tolerance.

The coning of the third stage motor prior to spacecraft separation was less than one degree and is believed well within the tolerance level of future missions. Evidence of chuffing, could not be detected.

The external case temperature levels measured during and after third stage operation (Figure 8) were within the specified maximum tolerance of 500°F for 200 seconds after third stage burnout. The only temperature which exceeded this value was recorded on the metal nozzle flange. Since the temperature requirement is based on maintaining the structural strength on the fiberglass case, the temperature of 502°F at 200 seconds on the nozzle flange does not invalidate maintaining of this specification.

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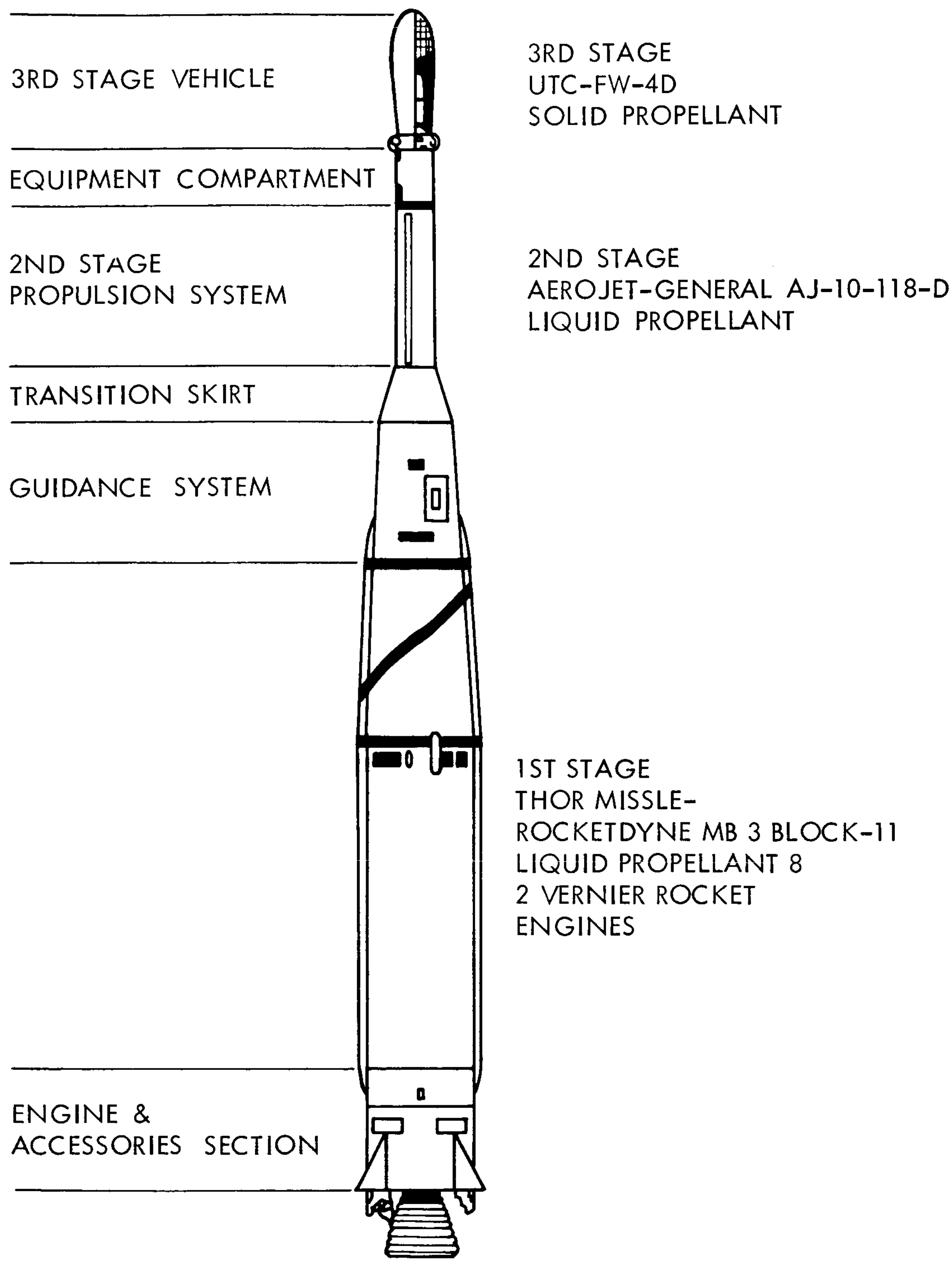


Figure 1–Delta DSV-3E-1 Outboard Profile

FW-4S ROCKET MOTOR

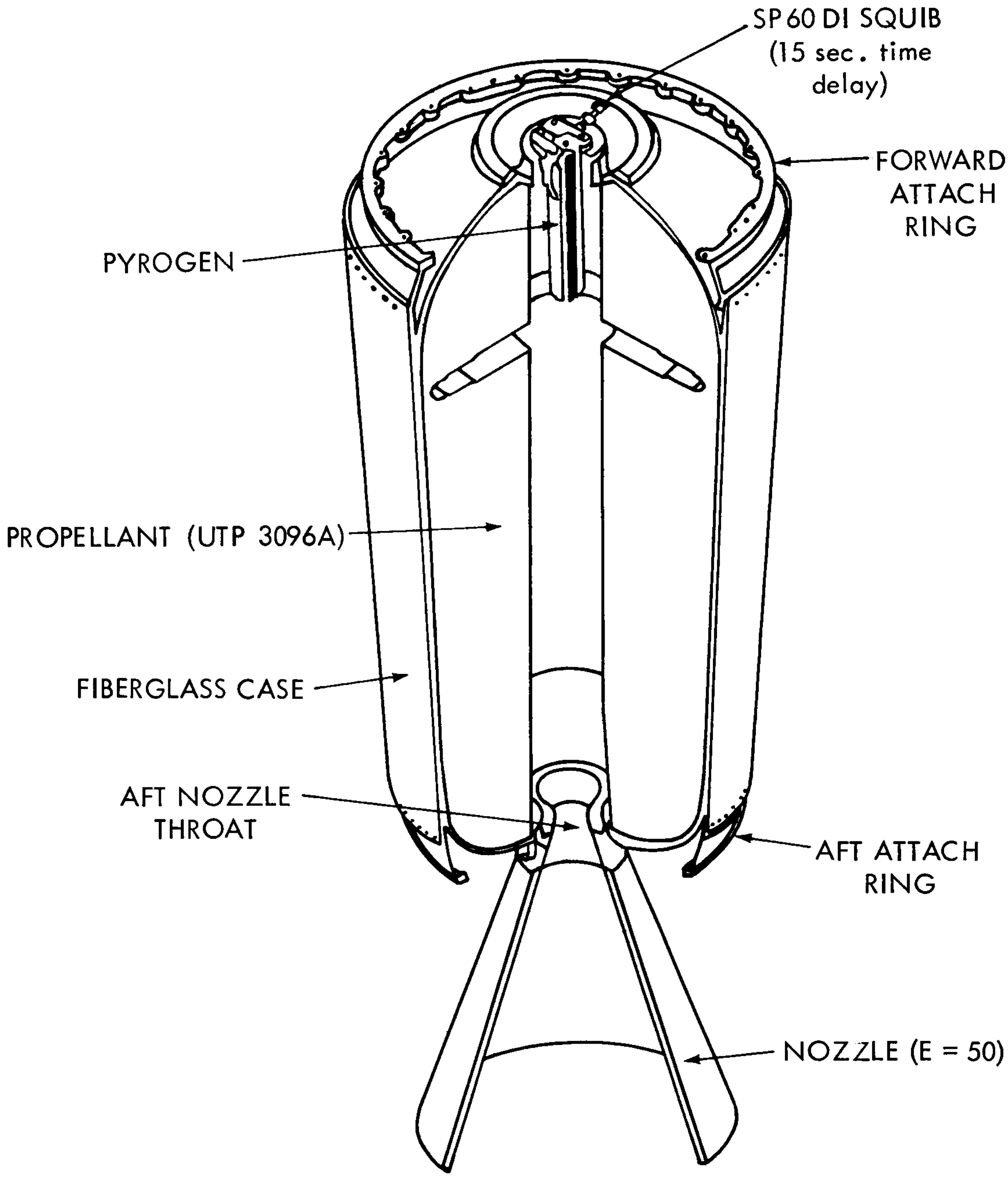
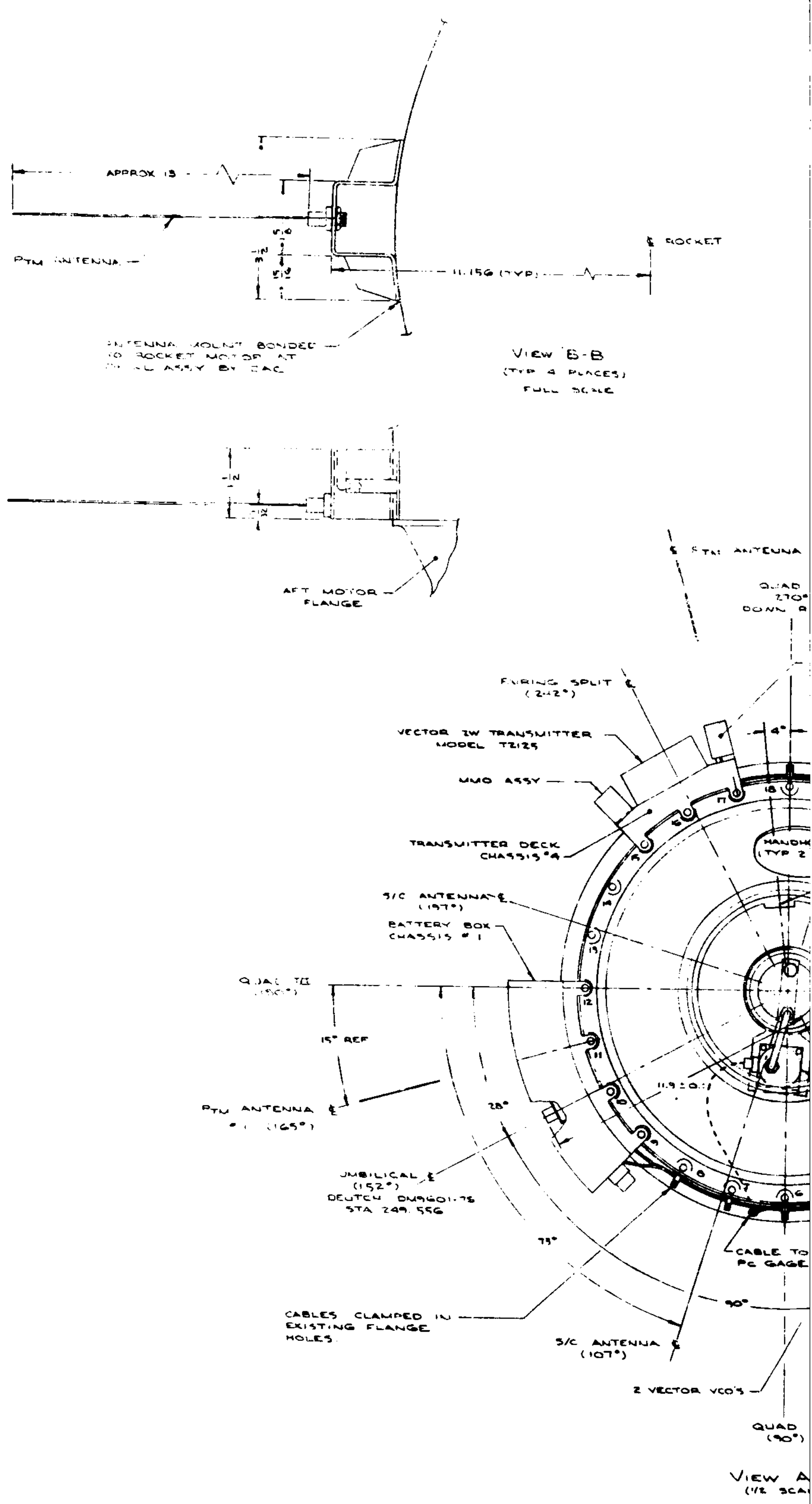
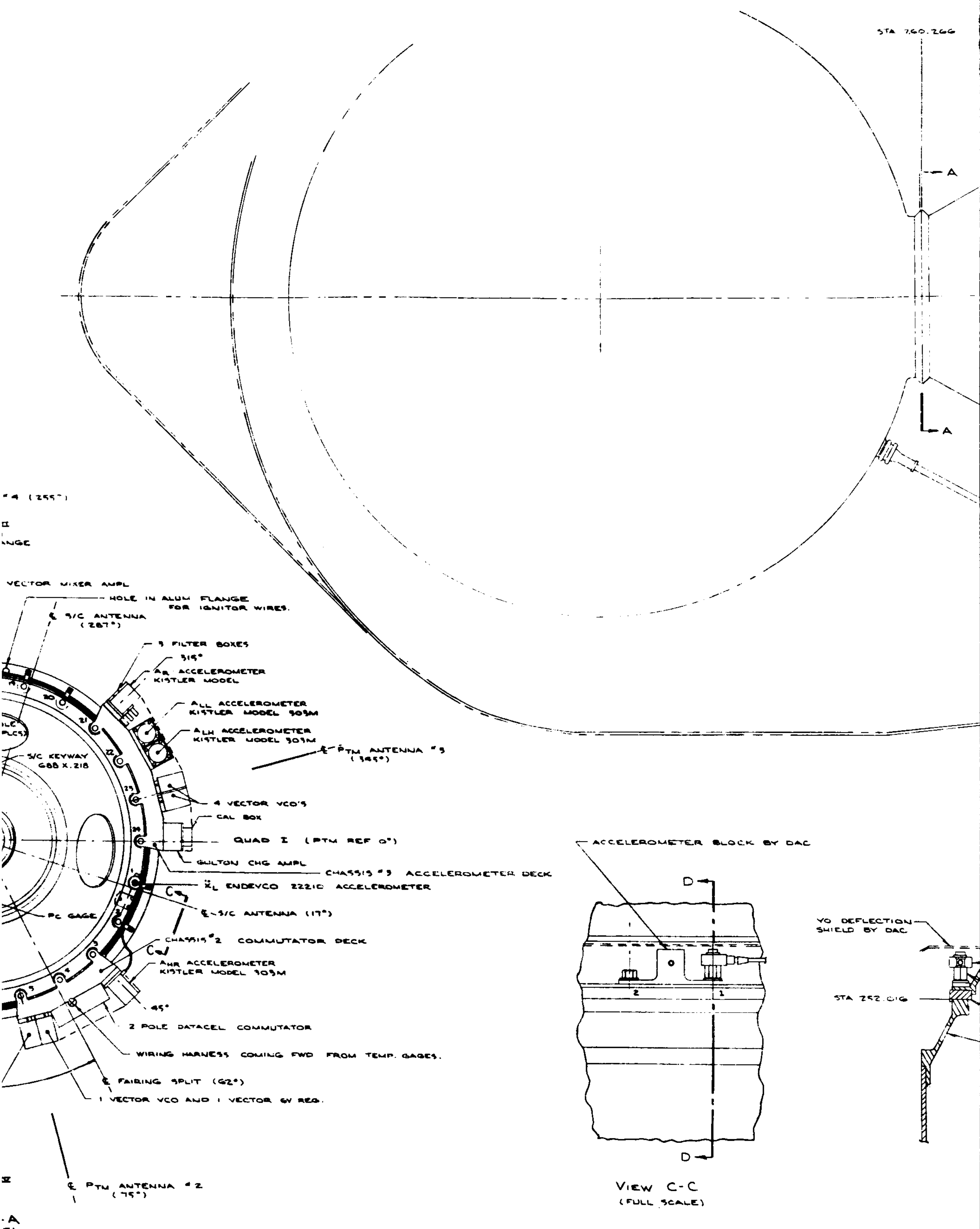


Figure 2–FW-4S Inboard Profile



APPROX 13
11.156 (TYP)
℄ ROCKET
View B-B
(TYP 4 PLACES)
FULL SCALE
AFT MOTOR FLANGE
FIRING SPLIT ℄ (242°)
VECTOR 2W TRANSMITTER MODEL T2125
MMO ASSY
TRANSMITTER DECK CHASSIS #4
S/C ANTENNA ℄ (197°)
BATTERY BOX CHASSIS #1
15° REF
28°
UMBILICAL ℄ (152°)
DEUTCH DM9601-7S
STA 249.556
75°
90°
CABLES CLAMPED IN EXISTING FLANGE HOLES
S/C ANTENNA ℄ (107°)
2 VECTOR VCO'S
QUAD (90°)



STA 760.266
A
A
#4 (255°)
II
NGE
VECTOR MIXER AMPL
HOLE IN ALUM FLANGE FOR IGNITOR WIRES.
℄ S/C ANTENNA (287°)
3 FILTER BOXES
315°
A_R ACCELEROMETER KISTLER MODEL
A_{LL} ACCELEROMETER KISTLER MODEL 303M
A_{LH} ACCELEROMETER KISTLER MODEL 303M
℄ P_{TM} ANTENNA #3 (345°)
S/C KEYWAY .688 X .218
4 VECTOR VCO'S
CAL BOX
QUAD I (PTM REF 0°)
GULTON CHG AMPL
CHASSIS #3 ACCELEROMETER DECK
$\ddot{X}_L$ ENDEVCO 2221C ACCELEROMETER
C
℄ S/C ANTENNA (17°)
P_C GAGE
CHASSIS #2 COMMUTATOR DECK
C
A_{HR} ACCELEROMETER KISTLER MODEL 303M
45°
2 POLE DATACEL COMMUTATOR
WIRING HARNESS COMING FWD FROM TEMP. GAGES.
℄ FAIRING SPLIT (62°)
1 VECTOR VCO AND 1 VECTOR 6V REG.
IV
℄ P_{TM} ANTENNA #2 (75°)
A
E)
ACCELEROMETER BLOCK BY DAC
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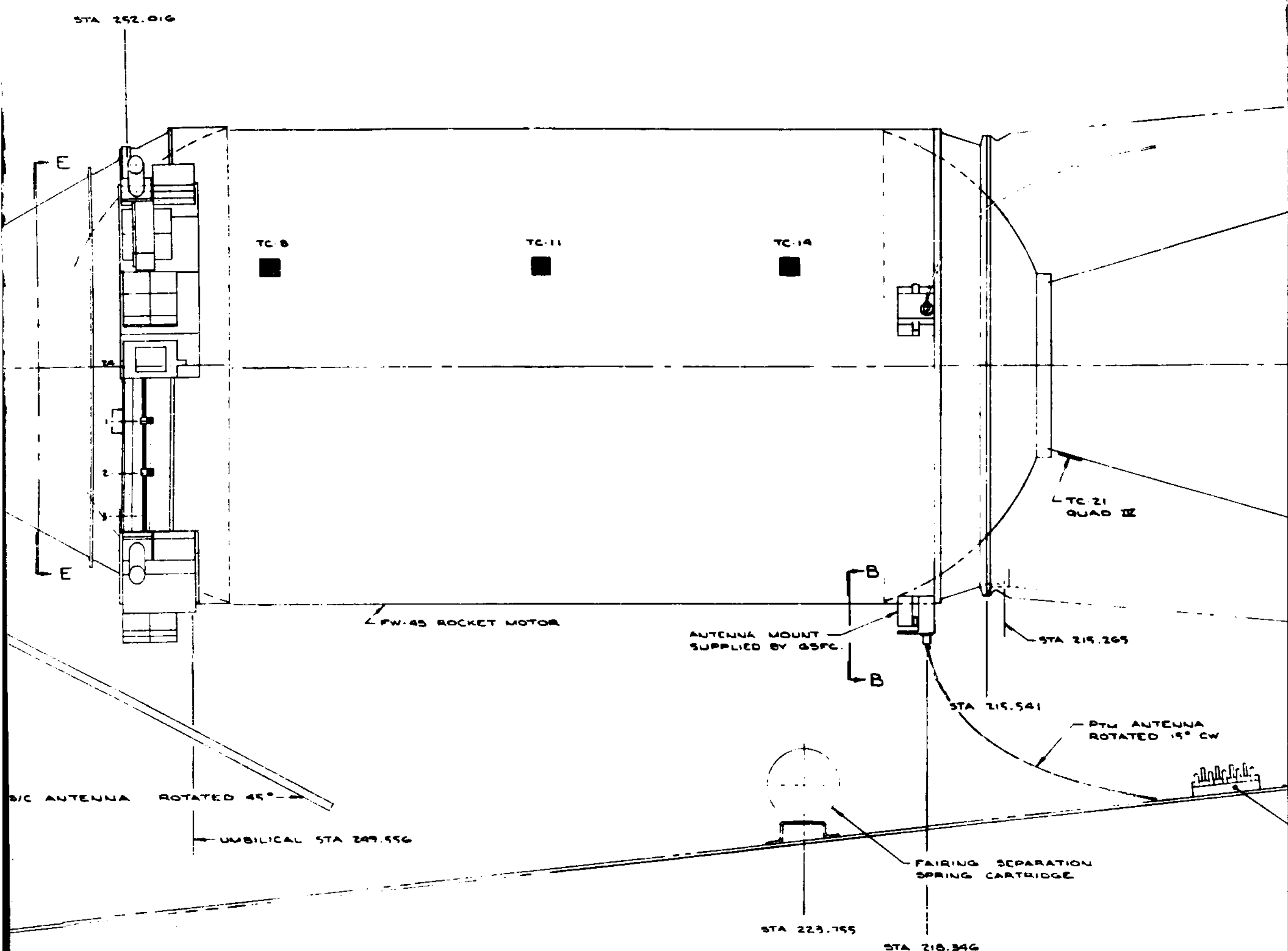
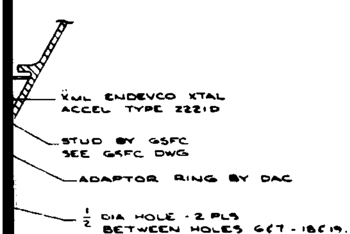
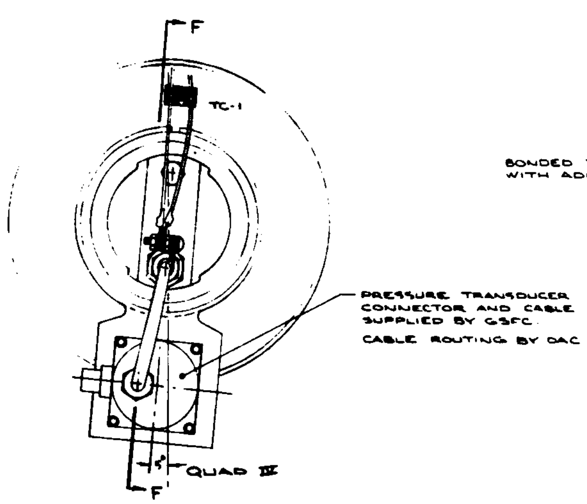
VIEW C-C
(FULL SCALE)
YO DEFLECTION SHIELD BY DAC
STA 252.016





SECTION D-D
SHOWING ENDEVCO ACCEL
(XML & MTD STUD)
(FULL SCALE)



VIEW E-E
(FULL SCALE)

BONDED TO ROCKET MOTO
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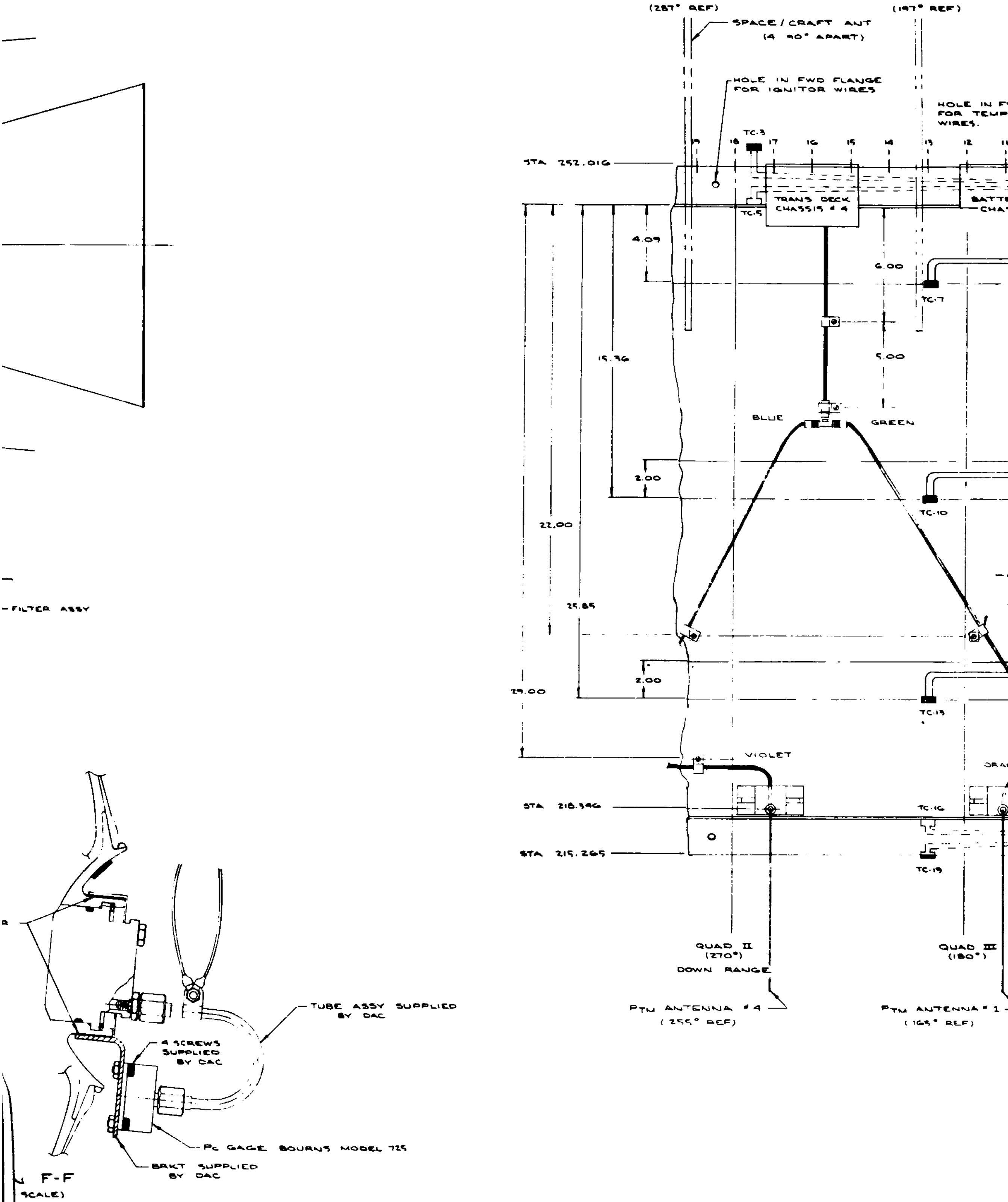


FILTER ASSY
TUBE ASSY SUPPLIED BY DAC
4 SCREWS SUPPLIED BY DAC
Pc GAGE BOURNS MODEL 725
BRKT SUPPLIED BY DAC
F-F
SCALE)
(287° REF)
(197° REF)
SPACE / CRAFT ANT (4 90° APART)
HOLE IN FWD FLANGE FOR IGNITOR WIRES
HOLE IN F
FOR TEMP
WIRES.
TC-3
TC-5
TC-7
TC-10
TC-13
TC-16
TC-19
STA 252.016
STA 218.346
STA 215.265
TRANS DECK CHASSIS # 4
BATTE
CHA
4.09
6.00
5.00
15.36
2.00
22.00
25.85
2.00
29.00
BLUE
GREEN
VIOLET
QUAD II (270°) DOWN RANGE
QUAD III (180°)
PTM ANTENNA # 4 (255° REF)
PTM ANTENNA # 1 (165° REF)

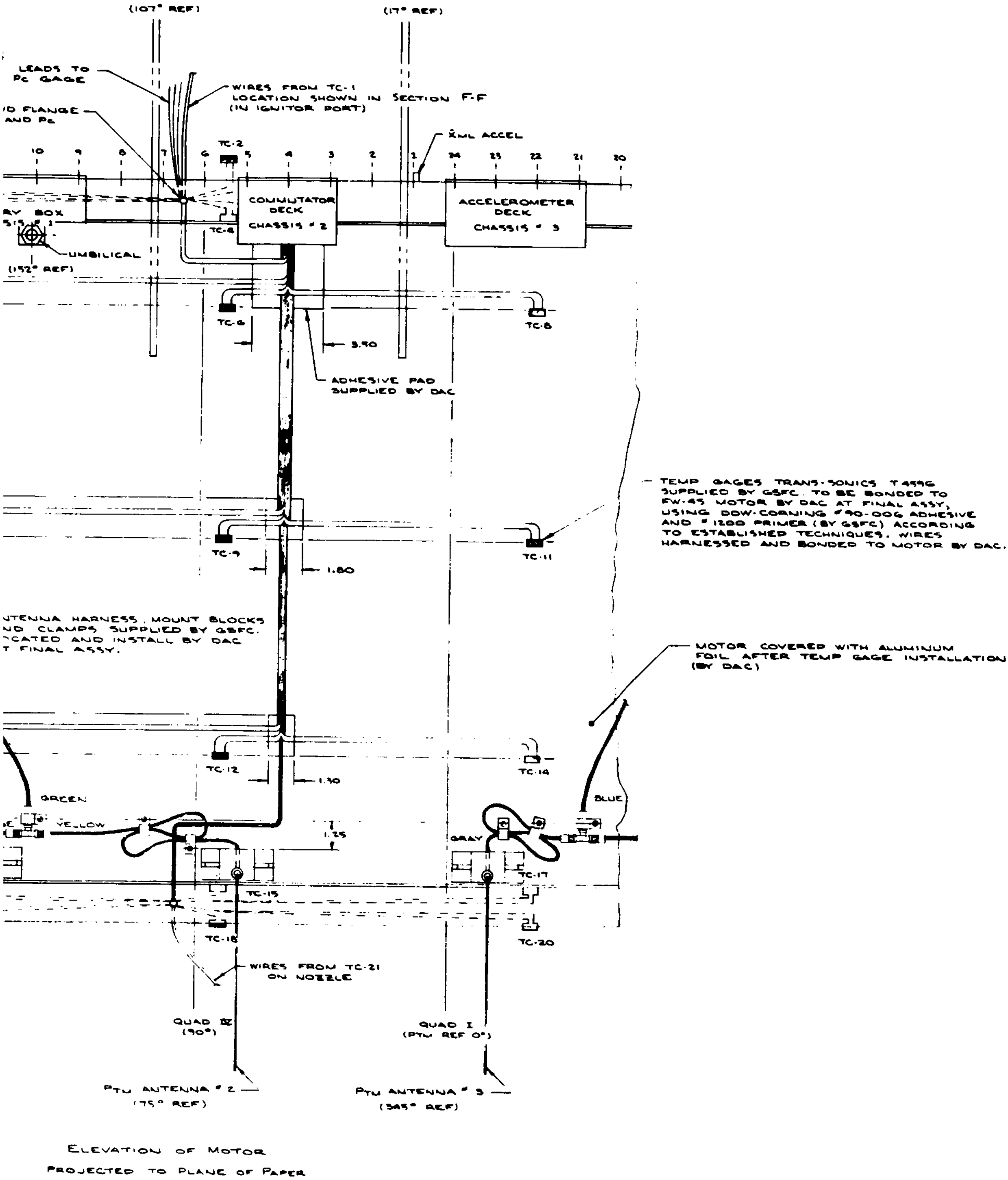


Figure 3—AE-B/PTM Location Drawing

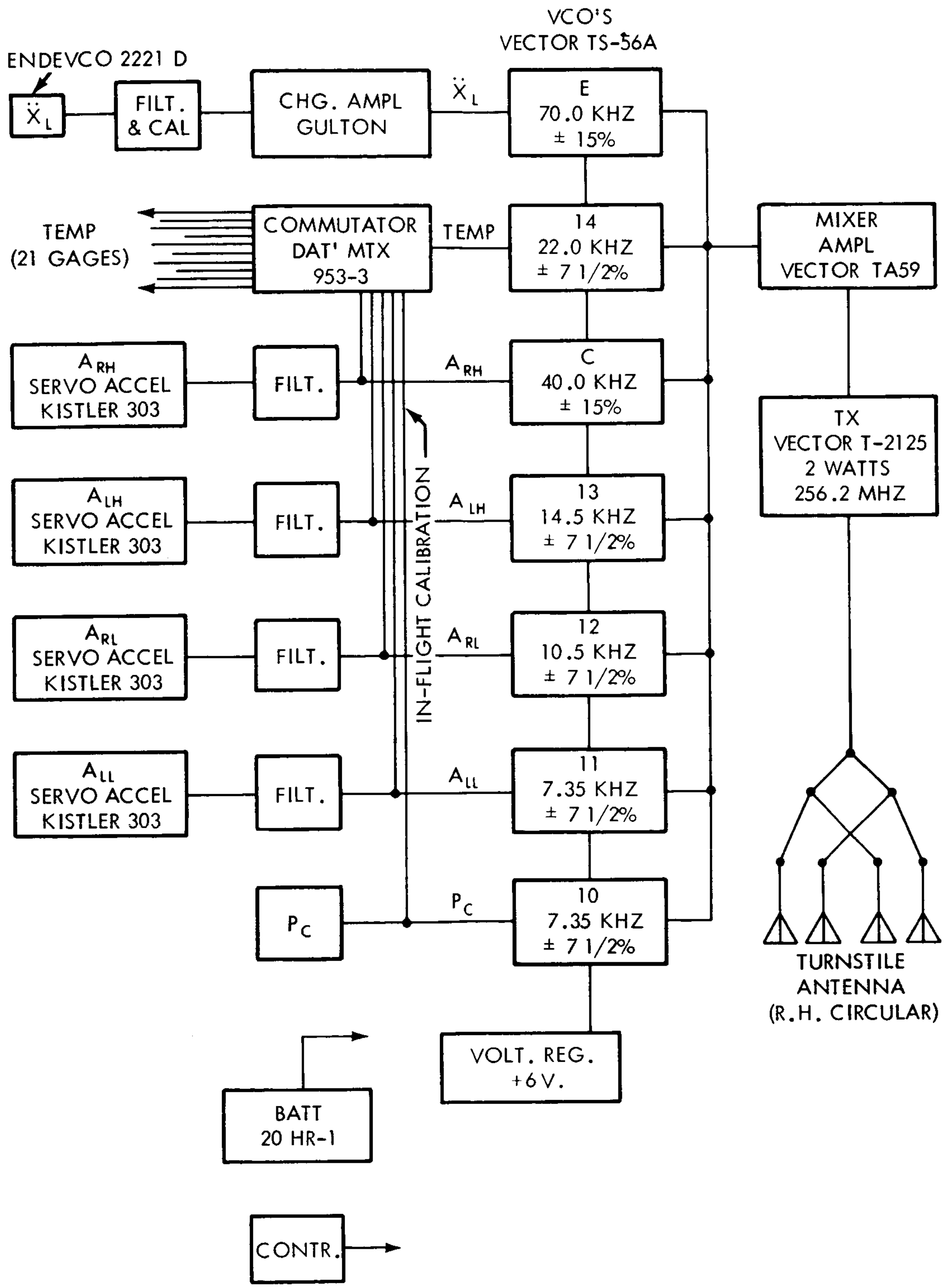
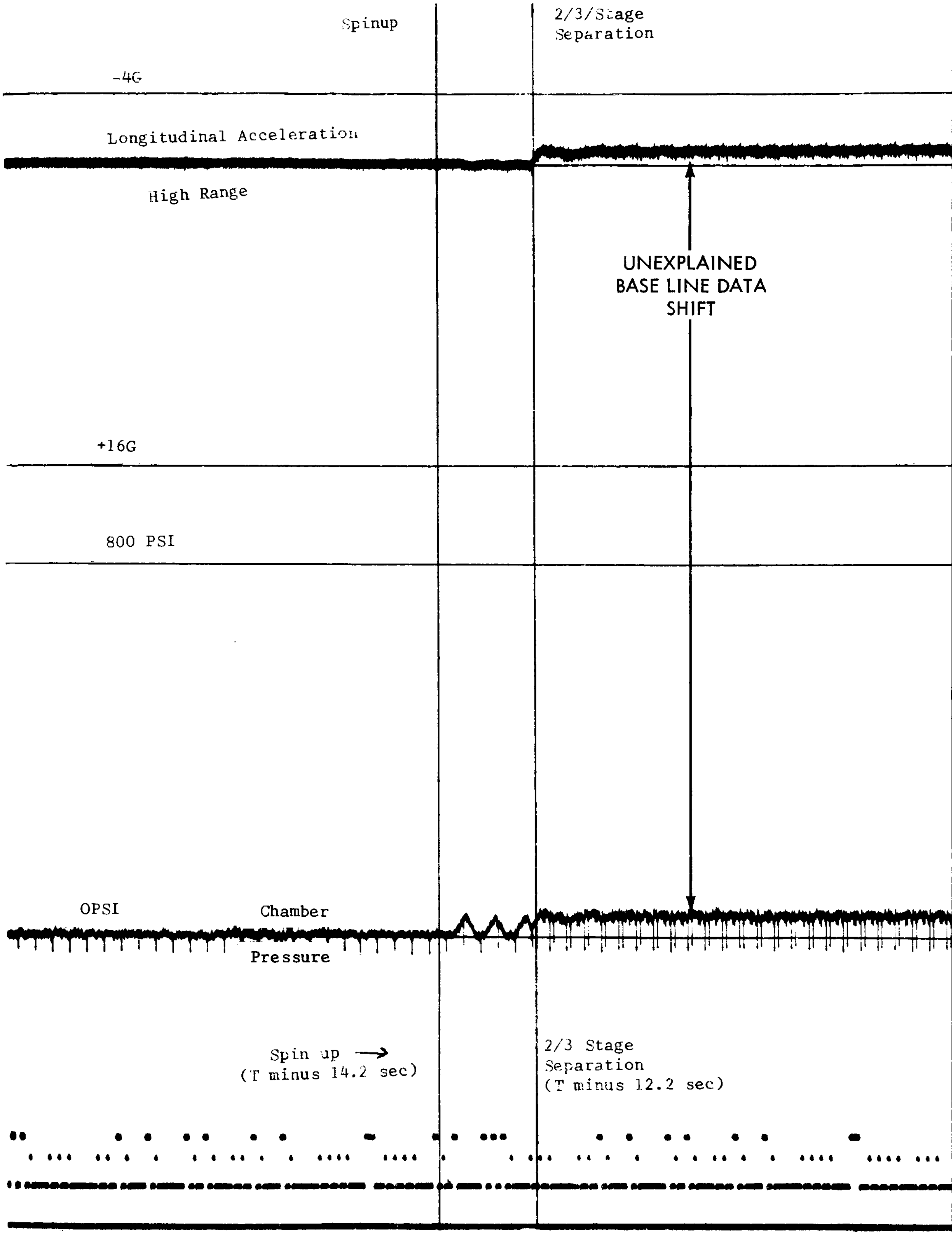
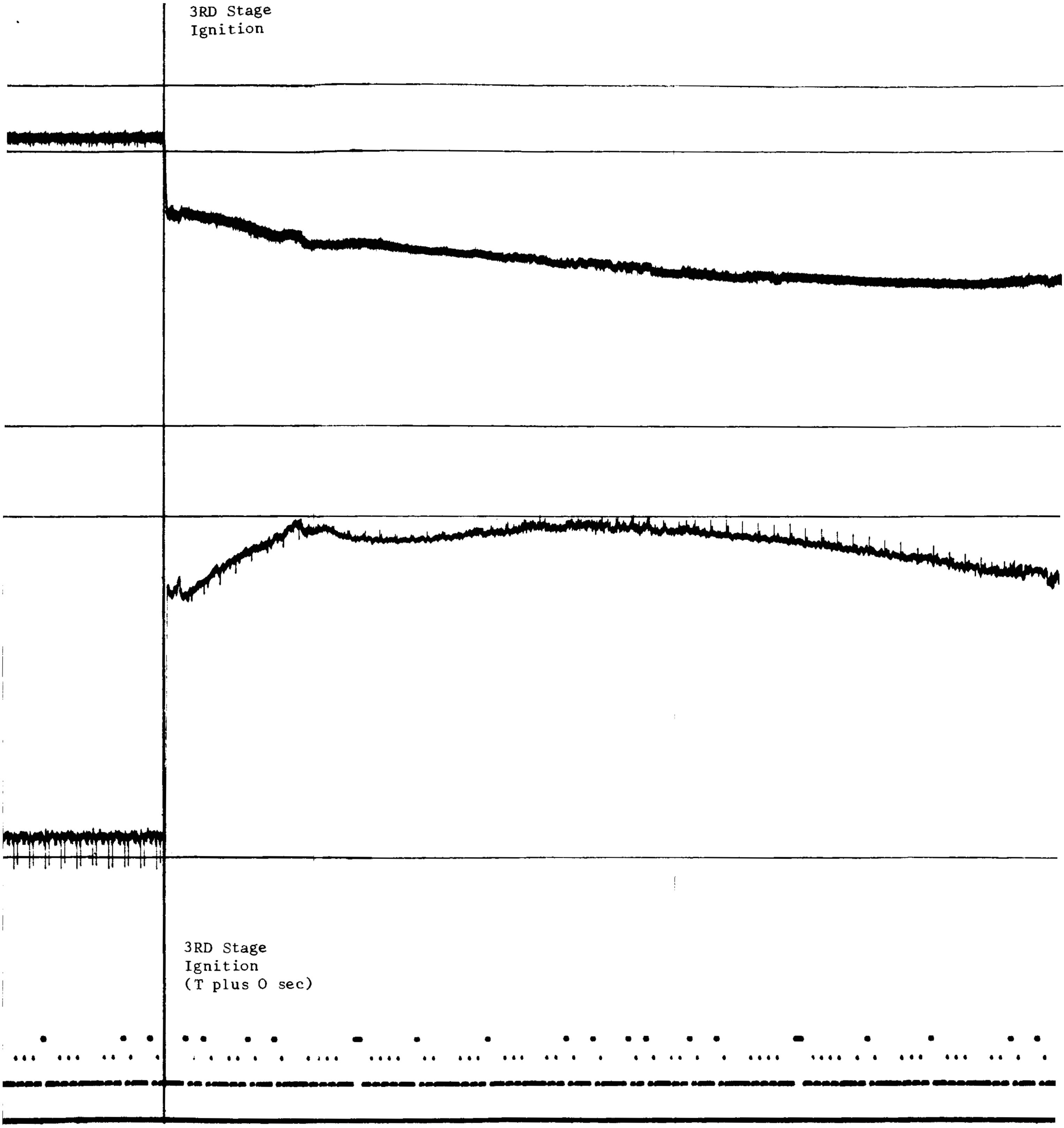
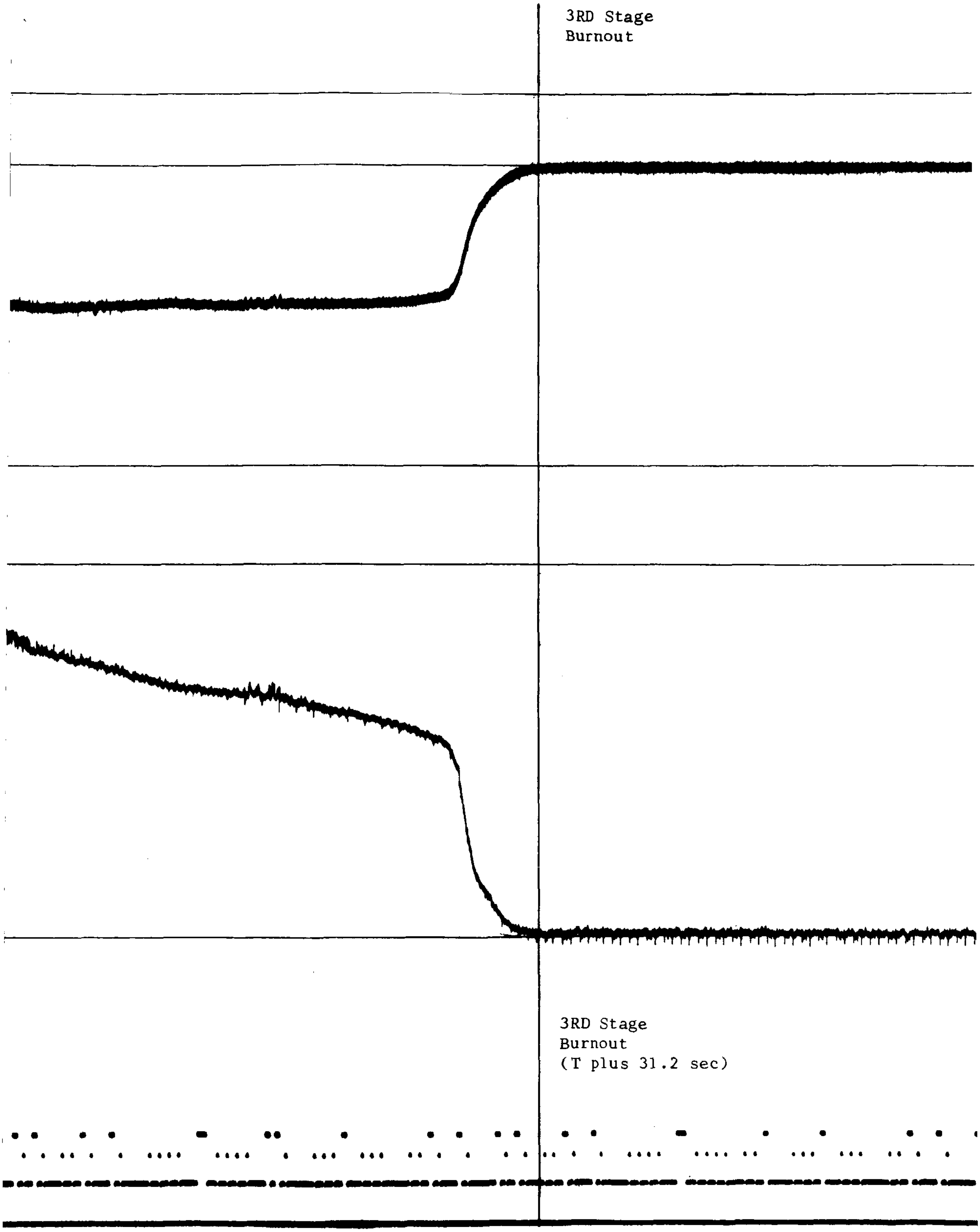


Figure 4–AE-B/PTM Block Diagram


Spinup
2/3/Stage
Separation
-4G
Longitudinal Acceleration
High Range
UNEXPLAINED
BASE LINE DATA
SHIFT
+16G
800 PSI
OPSI
Chamber
Pressure
Spin up
(T minus 14.2 sec)
2/3 Stage
Separation
(T minus 12.2 sec)


3RD Stage
Ignition
3RD Stage
Ignition
(T plus 0 sec)


3RD Stage
Burnout
3RD Stage
Burnout
(T plus 31.2 sec)

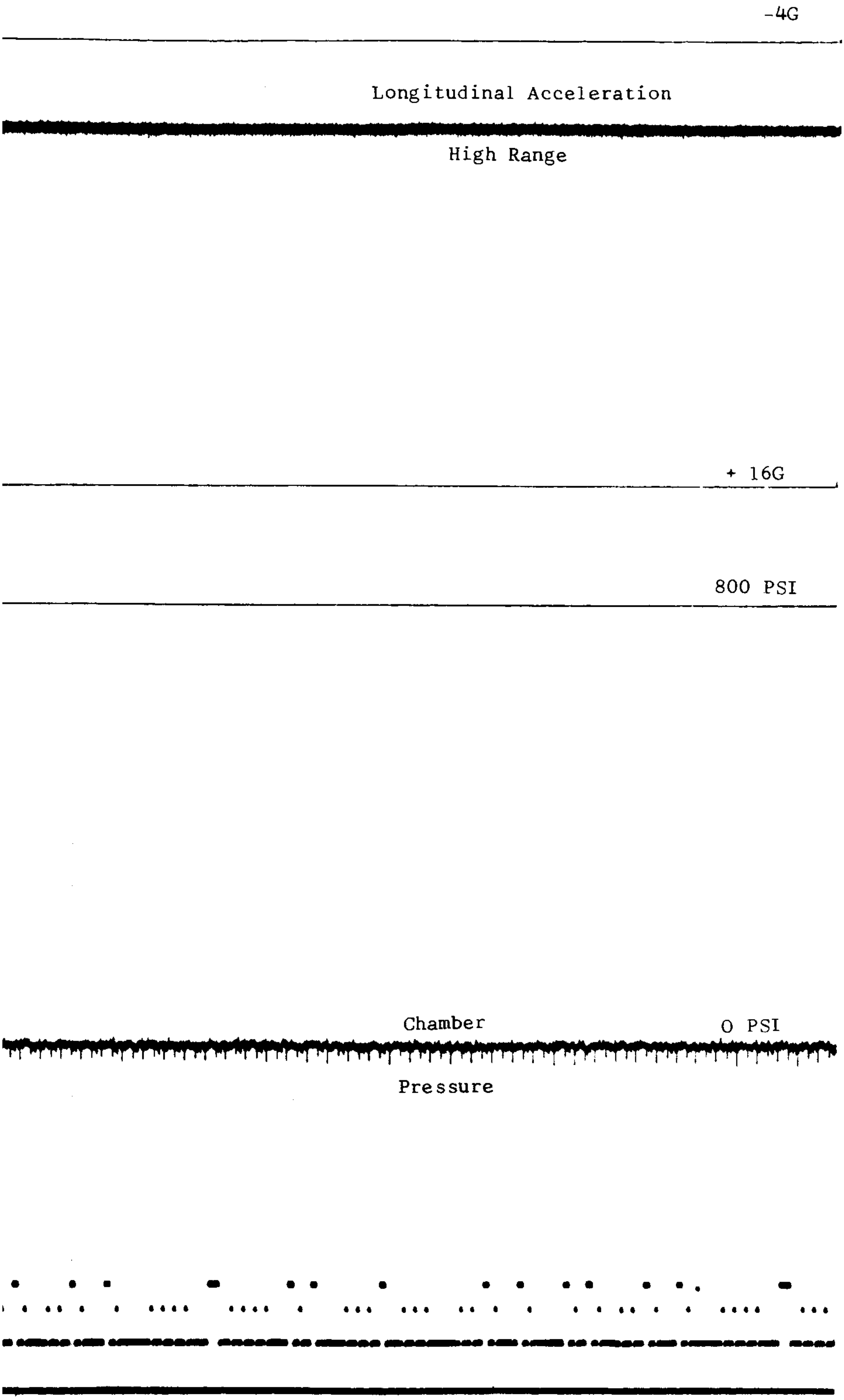


Figure 5a & 5b–Oscillograph Record of FW-4S Chamber Pressure and Longitudinal Acceleration

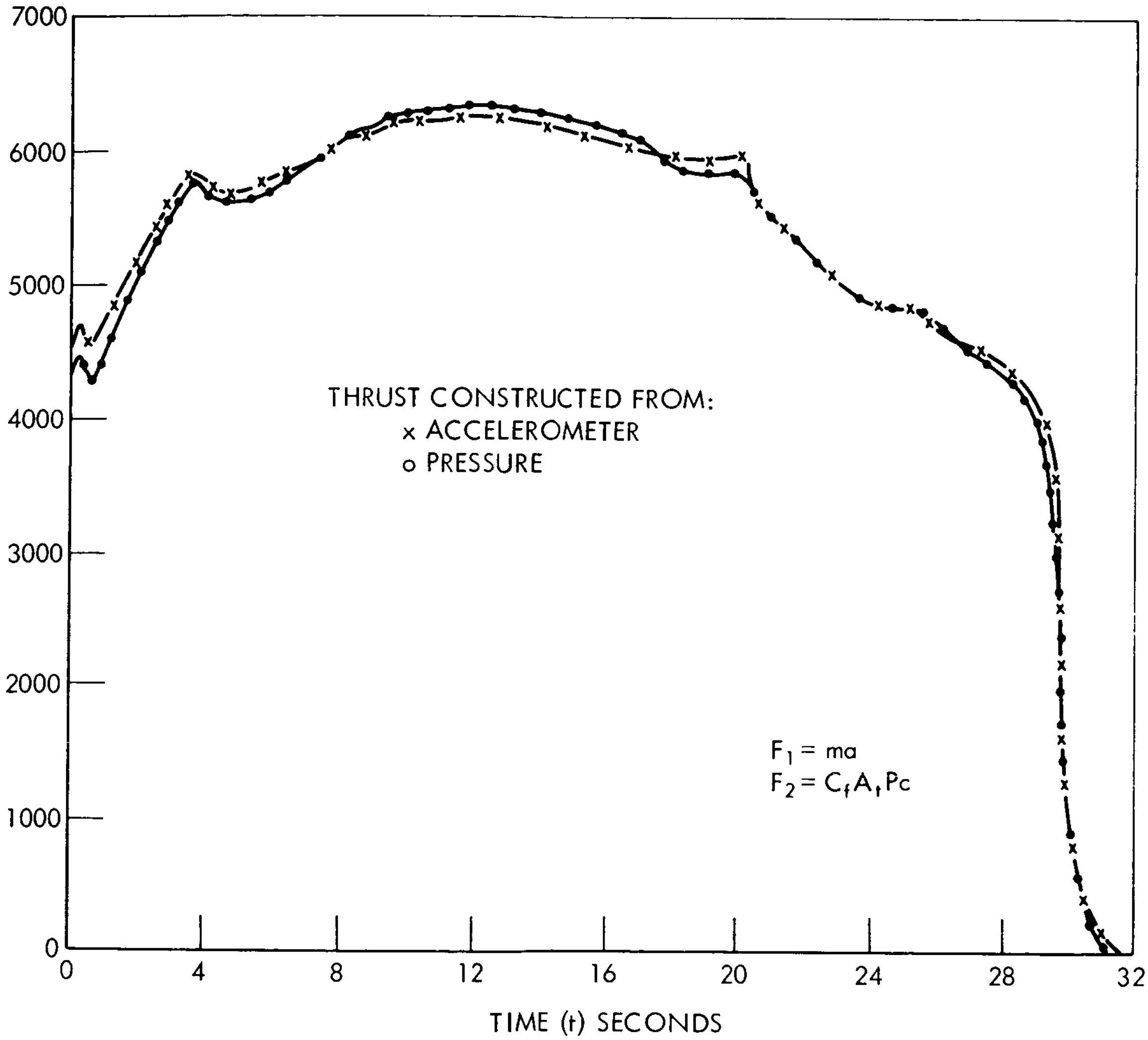
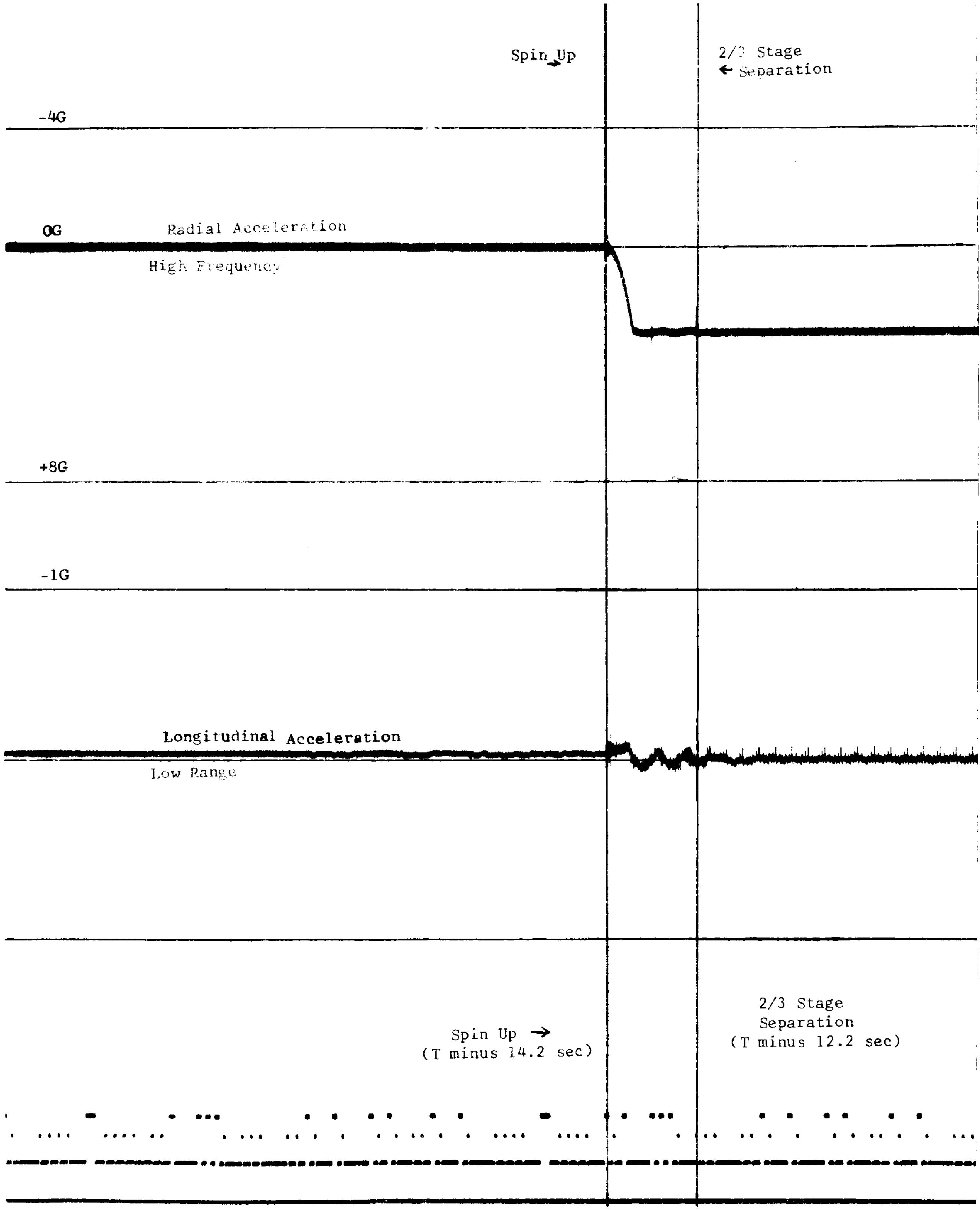
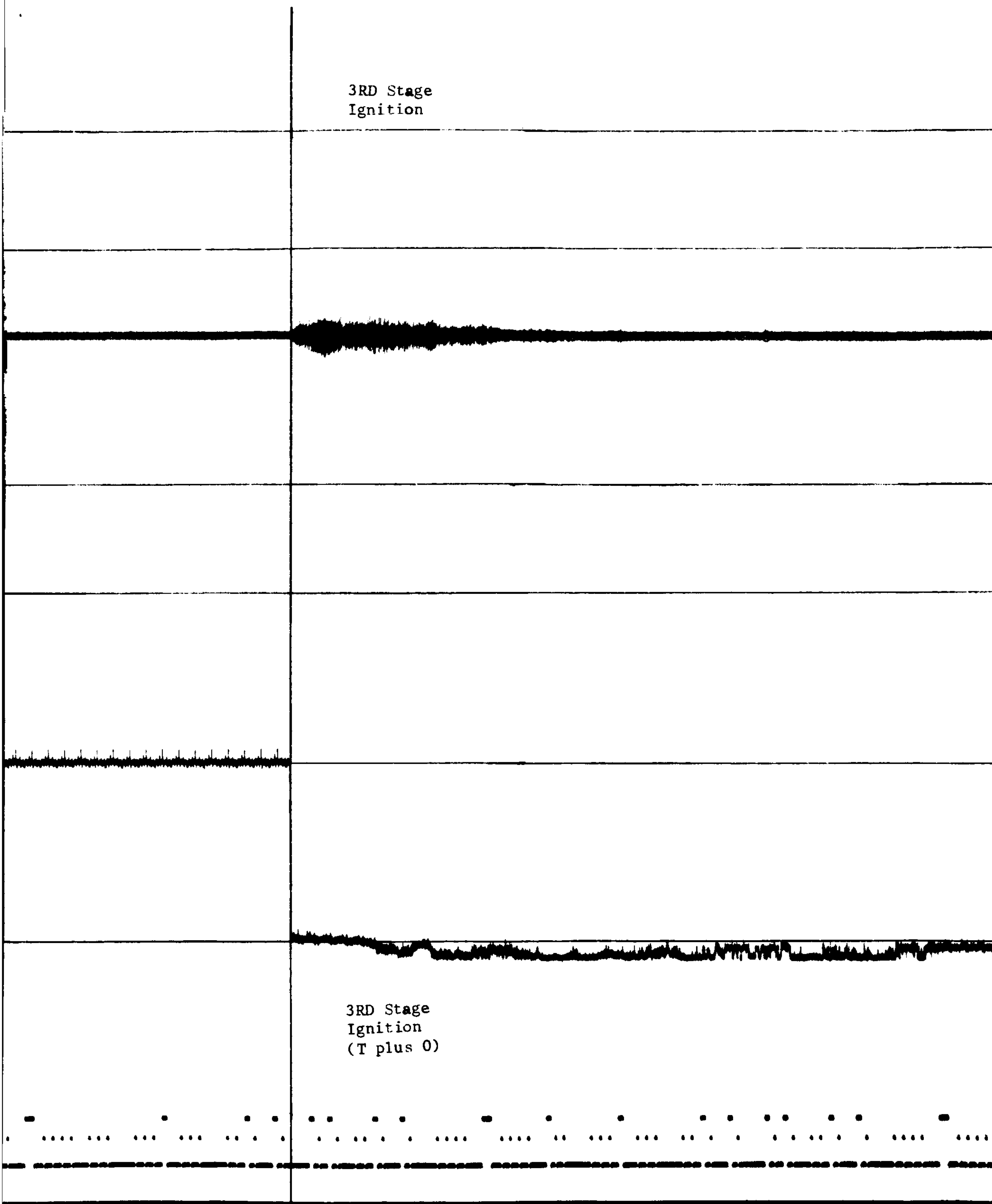
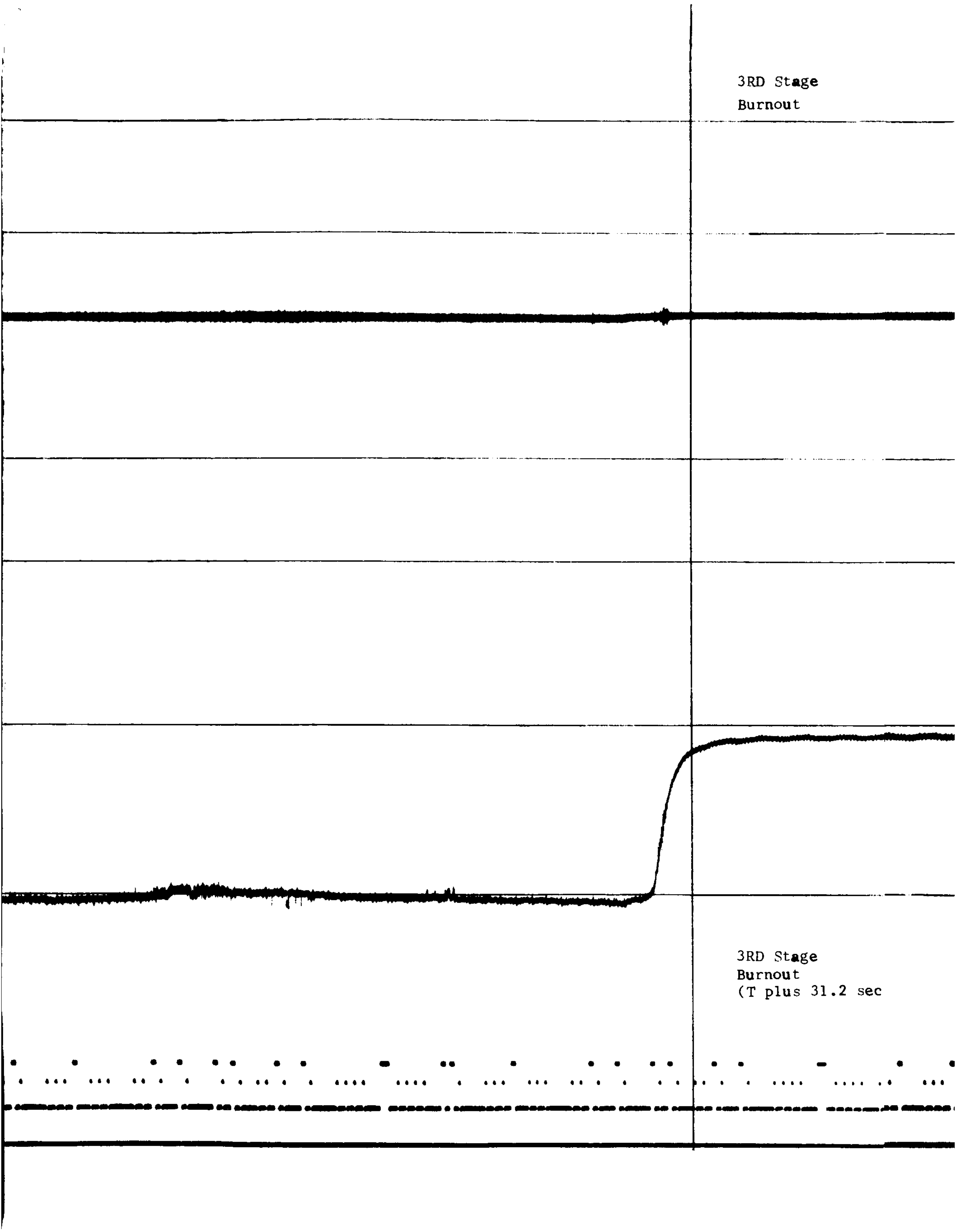
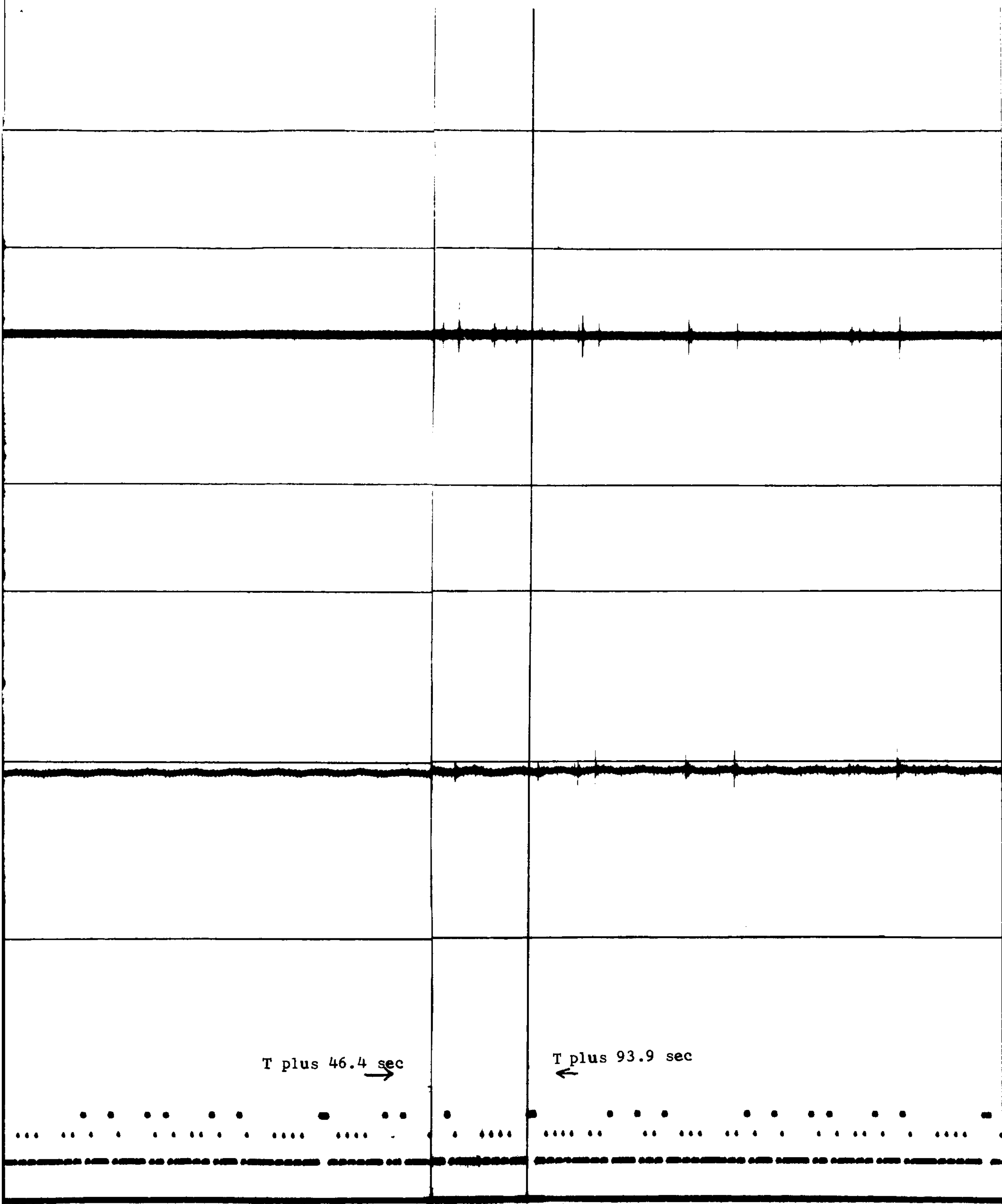


Figure 6–Comparison of Thrust Curves from Pressure and Acceleration Telemetered Data


Spin Up
2/3 Stage
Separation
-4G
0G
Radial Acceleration
High Frequency
+8G
-1G
Longitudinal Acceleration
Low Range
Spin Up
(T minus 14.2 sec)
2/3 Stage
Separation
(T minus 12.2 sec)


3RD Stage
Ignition
3RD Stage
Ignition
(T plus 0)


3RD Stage
Burnout
3RD Stage
Burnout
(T plus 31.2 sec


T plus 46.4 sec
T plus 93.9 sec

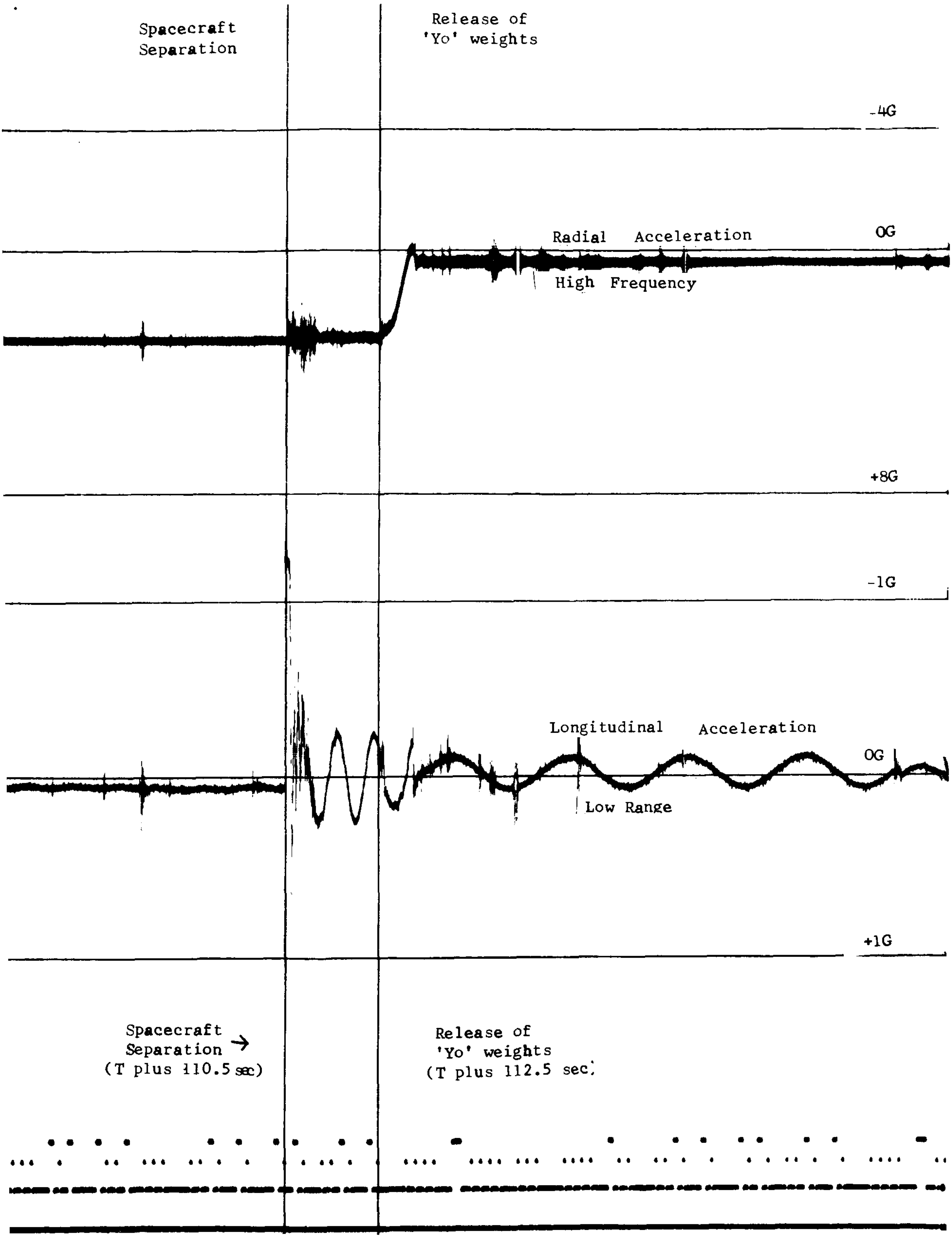


Figure 7a & 7b—Radial and Low Level Longitudinal Acceleration Records

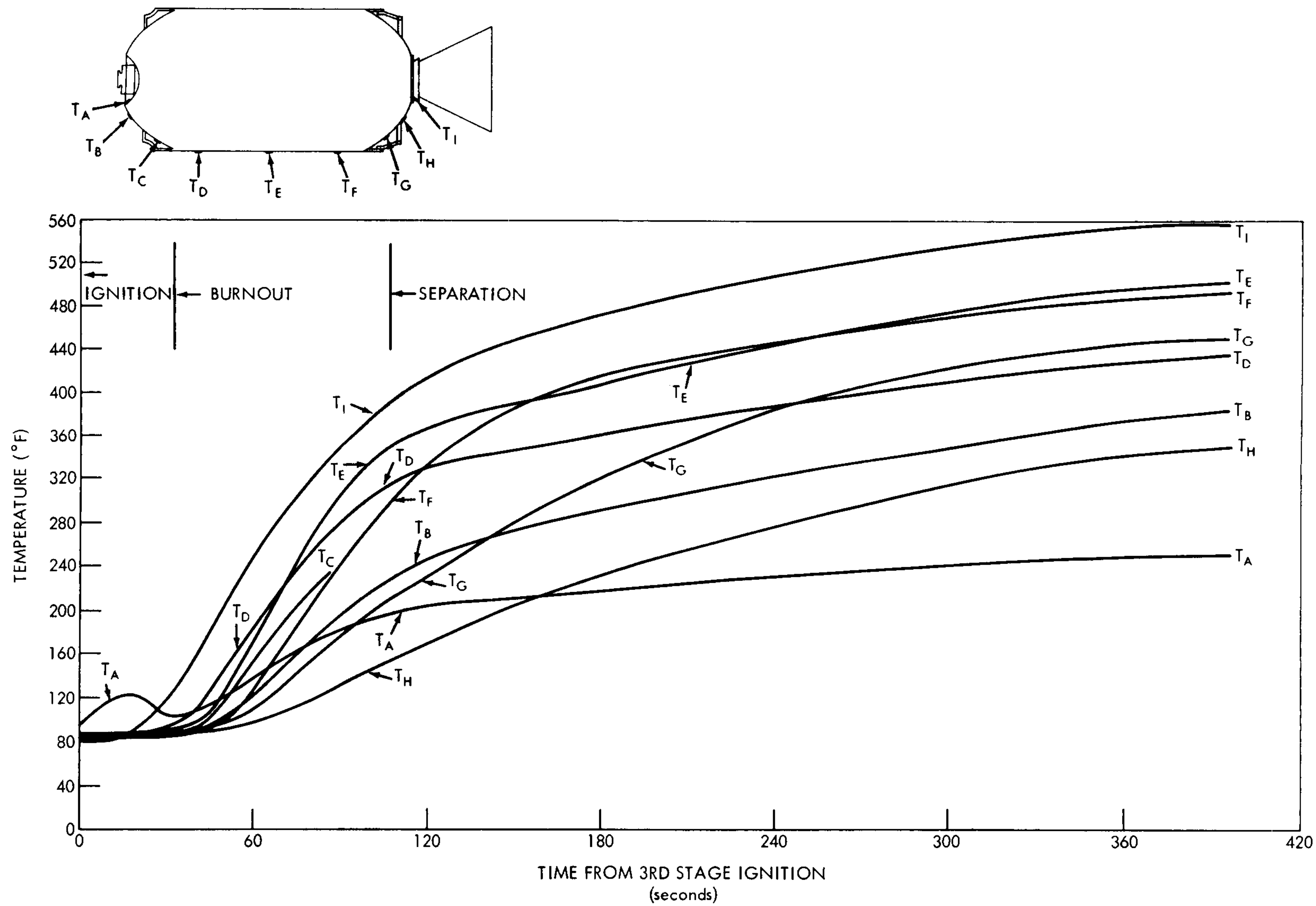


Figure 8–FW-4S External Cast Temperature